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A COST-CONSTRAINED DESIGN POINT FOR THE REVERSED-FIELD PINCH REACTOR (RFPR)*

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A broad spectrum of Reversed-Field Pinch Reactor (RFPR) operating modes are compared on an economics basis. An RFPR with superconducting coils and an air-core poloidal field transformer optimizes to give a minimum cost system when compared to normal-conducting coils and the iron-core transformer used in earlier designs. An interim design is described that exhibits a thermally stable, unrefueled, 21 s burn (burnup 50%) with an energy containment time equal to 200 times the Bohm time, which is consistent with present-day tokamak experiments. This design operates near the minimum energy state ($\Theta = B_\theta(r_w)/\langle B_z\rangle = 2.0$ and $F = B_z(r_w)/\langle B_z\rangle = 1.0$ from the High Beta Model) of the RFP configuration. This cost-optimized design produces a reactor of 1.5-m minor radius and 12.8-m major radius, that generates 1000 MWe (net) with a recirculating power fraction of 0.15 at a direct capital cost of 970 \$/kWe (1978 dollars).

I. INTRODUCTION

Optimization of previous Reversed-Field Pinch Reactor (RFPR) conceptual designs[1,2] have utilized the recirculating power fraction $\varepsilon = 1/Q_E$ as an object function. Maximizing Q_E generally leads to the smallest balance-of-plant costs for a given net electrical output, although the Q_E optimization may produce an economically non-optimal system. This concern has lead to the development of a general costing procedure to interface with the RFPR design codes which allows iteration to a system with minimum total cost. This cost model is flexible but comprehensive,[3] and has been used to evaluate earlier conceptual RFPR designs[1,2] as well as more-recent operating modes employing normal-conducting or superconducting magnet coils, air- or iron-core poloidal field systems, and various plasma burn cycles.

As illustrated in Fig. 1, the RFPR is a toroidal device of arbitrary aspect ratio in which a toroidal plasma current density is sufficiently high to permit ohmically heating to ignition; the poloidal field B_θ(T) associated with the ohmic-heating current provides the primary confinement. The presence of a conducting shell (or external conductors) eliminates unstable MHD modes that require wavelengths longer than the minor radius r_w(m).[4] Unlike q-stabilized systems ($q = 2B_z/j_z\mu_0 r_w > 1$), such as tokamaks and belt pinches in which unstable modes would require wavelengths longer than the major toroidal circumference $2\pi R$(m), considerably higher current densities j_z(A/m^2) are possible in the RFPR ($q < 1$). A toroidal bias field B_{z0}(1-2 T), trapped inside the

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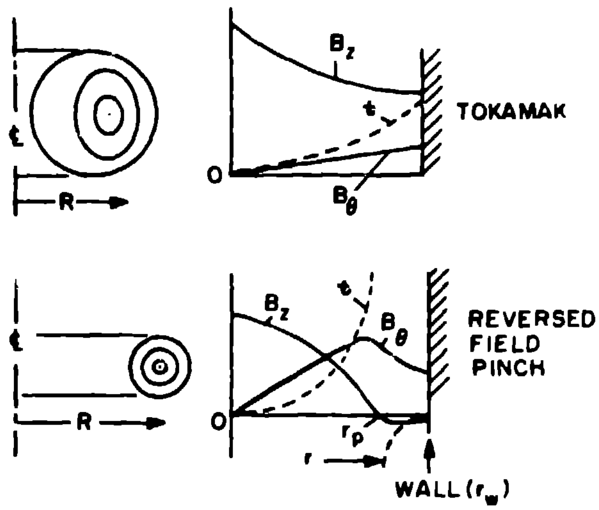

FIGURE 1. Field profiles for a Tokamak and Reversed-Field Pinch (RFP) showing the variation of toroidal B_z and poloidal B_θ fields. The rotational transform measures the field shear, which is considerably larger in the RFP.

plasma after ionization, is compressed by the increasing poloidal field while ultimately being reversed outside the plasma column (Fig. 1). A highly sheared field configuration results that stabilizes localized modes, according to the Mercier[5] criteria, and allows operation at poloidal betas β_θ up to ~50%.[6]

Reactor considerations of RFP confinement lead to a number of potential advantages when compared to q-stabilized systems. Ohmic heating to ignition by the primary containment current negates the need for auxiliary heating sources. The confining poloidal field, B_θ, varies inversely with the minor radius outside the plasma and reduces magnetic energy storage and magnet stresses when compared to devices that require uniform toroidal fields outside the plasma. The unrestricted aspect ratio R/r_w leads to an open system with minimized trapped-particle effects (better confinement) and easier construction and maintenance. Potential problems for the RFPR include startup, which may necessitate the plasma passing through unstable MHD states (similar to that in tokamaks) before a stable configuration is achieved, and the need for a conducting shell or external conductors. A copper shell, adjacent to the first-wall, is assumed to function (electrically) during the 0.1-s startup. External conductors subsequently maintain stability during the burn phase; for long feedback times (0.1 s) and a tractable number of modes to be stabilized, this approach appears technically feasible.[7]

The startup time is taken as 10% of the energy containment time (~1 s for a reactor) which is consistent with diffusion scaling from past and present LASL RFP experiments.[6] One of the goals of future experiments (e.g. ZT-40 at LASL) is the demonstration of diffusive scaling during startup in terms of energy confinement times for increased plasma temperatures and device sizes.

II. PLASMA ENGINEERING AND THEORETICAL CONSIDERATIONS

A. Plasma Model

The poloidal and toroidal magnetic-field profiles within the plasma are modeled, respectively, by the Bessel functions $A_\theta J_1(\alpha r)$ and $A_z J_0(\alpha r)$, which show good agreement with calculated MHD stable profiles.[2,6] The constants A_θ and A_z are determined by the conservation of total current and flux in the plasma.[2] Enforcing pressure balance and integrating over the isothermal plasma cross section allows the use of spatially-averaged parameters for the calculation of burn dynamics. A consistent calculation of the multi-species plasma (ions, electrons, and alphas) follows the plasma radius with time in conjunction with the voltages and currents in the plasma and associated electrical circuitry. Alpha-particle thermalization using a Fokker-Planck formalism, ohmic heating using classical resistivity, radiation (bremsstrahlung, cyclotron, and line) losses, and classical thermal conduction and particle diffusion are included in this time-dependent model.

A stability criterion is imposed. Ideal MHD calculations[6] predict stable pressure and field profiles for compression ratios as large as $1/x = r_w/r_p = 2.5$ with $\beta_\theta = 0.19$, where r_p(m) is the plasma radius at the zero point of the toroidal field. Poloidal betas of $\beta_\theta \sim 0.58$ are found stable at $1/x \simeq 1.4$ with a continuum of maximum betas between compressions of 2.5 and 1.4. The search for stable reversed-field profiles is facilitated by requiring the total toroidal flux remain positive. Earlier reactor calculations[1,2] imposed these stability criteria during the dynamic burn. Analytic work by Taylor[8-10] predicts that the lowest energy state for negligible beta inside a perfectly conducting shell is the reversed-field force-free configuration for $\Theta > 1.2$, where $\Theta = B_\theta(r_w)/\langle B_z\rangle$. Using classical diffusion coefficients, numerical calculations[11] have shown the existence of high-beta, stable states ($\beta_\theta = 0.3$-0.4) at $\Theta = 1.5$-2.0 and $F = 0.5$ to -1.0, where $F = B_z(r_w)/\langle B_z\rangle$; these conditions are satisfied for compression ratios of $1/x = 1.2$-1.4. The impact on the RFPR design of adjusting the burn constraints in accordance with ideal MHD theory (allows large values of Θ and F) compared to the constraints indicated by minimum-energy and resistive MHD calculations is examined in Sec. III.C.

B. Energy Balance and Operating Considerations

A realistic and detailed engineering energy balance is computed to optimize the system economics. Field energy is transferred on a $\tau_R = 0.1$-s timescale to the poloidal and toroidal field coils by the Energy Transfer and Storage (ETS) system with a 95% efficiency.[12] This energy partitions between vacuum field energy, transport and eddy-current losses in the blanket and magnet coil, ohmic heating, and field energy trapped within the plasma. The plasma burn restores a portion of the field energy to the ETS system by direct-conversion (high-β plasma expansion) work. Neutron, radiation, and conduction energies are deposited as high-grade thermal energy in the blanket. The magnetic field trapped in the plasma at the end of the burn is assumed to be resistively dissipated and, along with the residual plasma internal energy, is deposited at the first wall during the quench period. The total energy delivered to the blanket and first wall is converted with a thermal efficiency of $\eta_{TH} = 0.4$, and a fraction $\varepsilon = 1/Q_E$ of the resultant gross electric power is recirculated. Auxiliary plant requirements are taken to 7% of the gross electric power output, P_{ET}.

Major changes in operation, construction, and cost result when considering iron- versus air-core poloidal field systems and normal versus superconducting coils. The maximum field at the coil is typically less than 3 T, which results in a maximum field change of 30 T/s for a 0.1-s startup. This rate-of-change and absolute magnitude of magnetic field represent near-term technology[13] for NbTi superconductors; cost optimizations based upon both normal and superconducting coils have been determined. An iron- versus air-core transformer significantly changes the coupling between the poloidal field coil and the plasma. An equivalent circuit for the poloidal field system, shown in Fig. 2, is represented by the parallel connection of a capacitor (nomopolar generator) and the inductors L_{IN} and L_{EX} associated, respectively, with the regions internal and external to the poloidal field coil. For an air-core system $L_{EX} \sim L_{IN}$, while L_{EX} is considered infinite for an unsaturated iron core. The iron core ideally couples the current in the primary coil (I_C) to the plasma current ($I_C = I_P$) and requires a total stored energy in the homopolar generators of $L_{IN} I_P^2/2$. For an air core the current change in the poloidal field coil must be $L_{EX} I_C = (L_{EX} + L_{IN}) I_P$ which gives $I_C = 2I_p$ if $L_{IN} = L_{EX}$. For bipolar current operation (similar to that in tokamaks) the maximum current in the poloidal field coil is comparable to the iron-core system. The current for the air-core case remains in the coil between burn

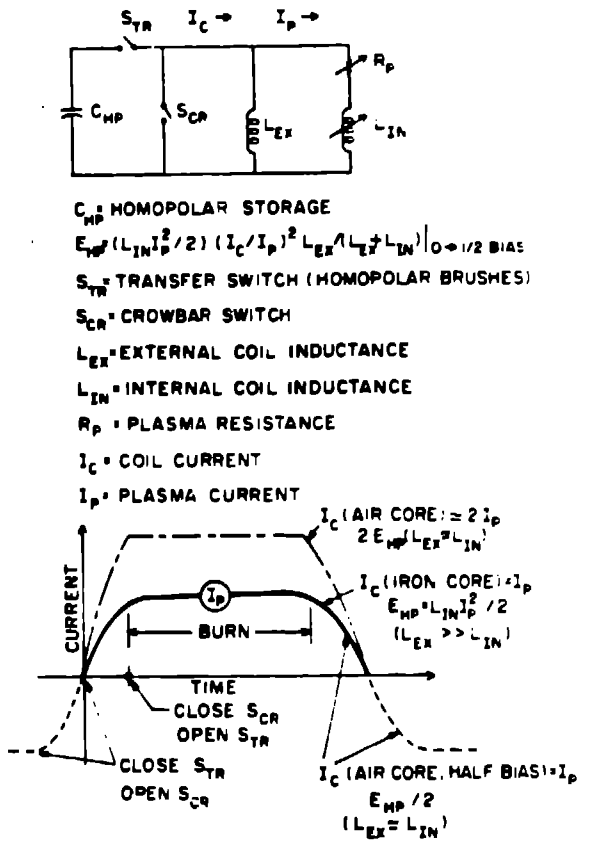

FIGURE 2. Equivalent circuit and current waveforms for the poloidal field system. An iron-core system implies $L_{EX} \rightarrow \infty$ and $I_C = I_p$, while for an air-core system a bipolar current is shown along with a case with no initial bias ($I_C = 2I_p$ for $L_{EX} = L_{IN}$).

periods since the presence of the hot plasma makes extraction difficult. Assuming $L_{IN} = L_{EX}$, a homopolar generator used as a transfer capacitor to change symmetrically the current from plus to minus requires an energy store equal to half that required by the iron-core case. Elimination of the large iron core (~1000 V s flux change required) appears economically desirable, although current flowing in the coils between burn pulses may require superconducting coils to minimize ohmic losses. This approach was first proposed by the Culham RFPR design group[14] and has been adopted by this study.

III. COST OPTIMIZATION

A. Description of Cost Model

Economic guidelines developed by Battelle Pacific Northwest Laboratories[3,15] are used for the costing framework. The difficulties in comparing various cost models has lead to the development of this common costing procedure and should provide the needed uniformity in assessing different concepts. The costing guidelines describe uniform accounting categories and procedures, although a uniform cost data base is yet to be adopted. A cost data base, therefore, has been generated by LASL to provide an interim optimization tool and to facilitate comparisons. It is emphasized that absolute cost values are intended only for the intercomparison of reactor designs and are not intended for absolute comparisons with existing energy technologies on the basis of present costs.[15]

The total capital cost of the plant is comprised of direct, indirect, and time-related (escalation and interest) costs. Direct costs are quoted in 1978 prices, result from the purchase of materials, equipment and labor, and take into account allowances for spare parts and contingencies. Indirect costs, taken as a percentage of the direct costs, result from support activities necessary to complete the project and are divided into three major accounts: 15% for construction facilities, equipment, and services; 15% for engineering and construction management services; and 5% for taxes, insurance, staff training, and plant startup. Escalation and interest are computed as a percentage of the direct plus indirect costs assuming a 10 year construction period. Aggregrate percentages of 33.8% and 49.4%,[15] respectively, result for an escalation rate of 5% and interest rate of 8%. Having determined the total capital cost c_D($/kWe), the power cost c_p (mills/kWeh) is computed on the basis of a 15% return on capital investment, an added 2% of the total capital cost for operating expenses and a power factor of 0.85.

B. Cost Optimization of Earlier RFPR Designs

Previous conceptual designs (RFPR-I)[1,2] were based on normal-conducting coils and an iron-cored poloidal field transformer. One design (RFPR-IA) used a 50%-50% DT fuel mixture (2.0 mTorr) that was ohmically heated to ignition by a 40-MA toroidal plasma current. Using a maximum plasma compression of $1/x = 2.5$ (at $\beta_\theta \sim 0$) in a 2-m minor radius device yields an experimentally achievable[6] current density of 20 MA/m^2. The plasma temperature increases by alpha-particle heating to ~ 30 keV in 1.1 s at which time $\beta_\theta \sim 0.35$; the plasma is subsequently expanded to the wall by reducing the plasma current to avoid stability-related beta limits ($\beta_\theta < 0.5$ at the wall radius). A total plasma burnup of 11% produces a 2 MW/m^2 wall loading with a cycle time of 8.6 s. Power costs c_p(mills/kWeh), direct costs c_D($/kWe), and Q_E versus the sum of toroidal and poloidal coil thicknesses are shown in Fig. 3 for the RFPR-IA (50%-50% DT, normal coils) design. In all cases the toroidal coil thickness is 20% of the total, giving comparable current densities in each room-temperature coil with a conductor filling fraction of 0.7. A short, vigorous burn is characteristic of this operating mode and results in the ohmic losses being a relatively small contribution to the recirculating power fraction; a total coil thickness of 0.4-0.6 m for the iron-core system is adequate. The RFPR-IA air-core system, using a bipolar current change (Fig. 2) incurs ohmic losses during the dwell time between burn pulses and optimizes at a much larger coil thickness of 1.5 m. The power costs for the bipolar, air-core system shown in Fig. 3 are reduced from 110 mills/kWeh to 89 mills/kWeh, however, when the massive iron core is eliminated in conjunction with a 50% reduction in the required ETS system.

Further reduction in the system costs can be realized by increasing Q_E, which minimizes the balance-of-plant costs. A large fraction ($\sim 50\%$) of the recirculating power in the (RFPR-IA) 50%-50% DT case is attributable to the resistive loss of field energy trapped inside the plasma during the quench. A larger fusion energy release (prolonged plasma burns) for a given investment of field energy is necessary to increase Q_E. An earlier conceptual design[1,2] (RFPR-IB) used a 90%-10% DT fuel mixture (1.25 mTorr) in which burnup of the fuel provides an inherent temperature limiting mechanism and control. The prolonged RFPR-IB burn (6.9 s) requires a smaller (30 MA) current to achieve a 1.54 MW/m^2 wall loading for a cycle time of 11.9 s in a 2-m radius device using a maximum plasma compression of $1/x = 2.5$ (at $\beta_\theta \sim 0$). The plasma temperature rises to

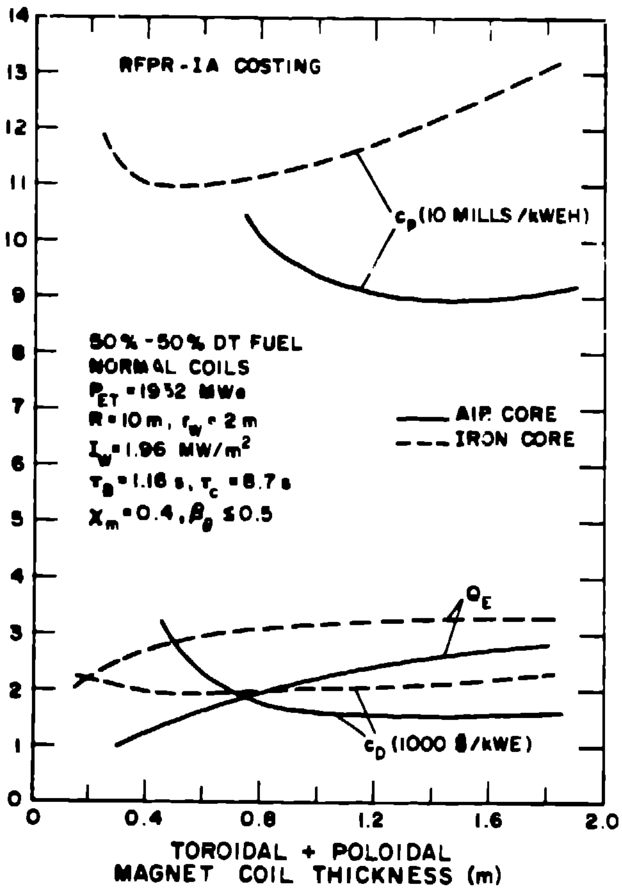

FIGURE 3. RFPR-IA costs for a 50%-50% DT fuel mixture for which β_θ control is provided by premature quench, resulting in a burnup of 11%. Ideal MHD stability criteria allow a maximum compression of $1/x \sim 2.5$ (Θ = 8, F = -2). Air- and iron-core poloidal systems with normal conducting coils are compared on a cost basis.

~50 keV in 3 s and remains relatively constant during the burn as a result of fuel burnup.

Costing results for the RFPR-IB (90%-10% DT, normal coils) are given in Fig. 4 along with Q_E curves. The large cost advantage in using a bipolar air-core rather than iron-core transformer again results. A cost reduction from 89 to 81 mills/kWeh (at the cost optimum) from the 50%-50% (RFPR-IA) to the 90%-10% (RFPR-IB) DT case is caused primarily by the ~40% reduction in required energy storage (40 MA to 30 MA) and the increase in Q_E from 2.7 to 3.4. The relatively small increase in Q_E results from the large ohmic losses incurred during the longer RFPR-IB burn cycle; as a consequence the

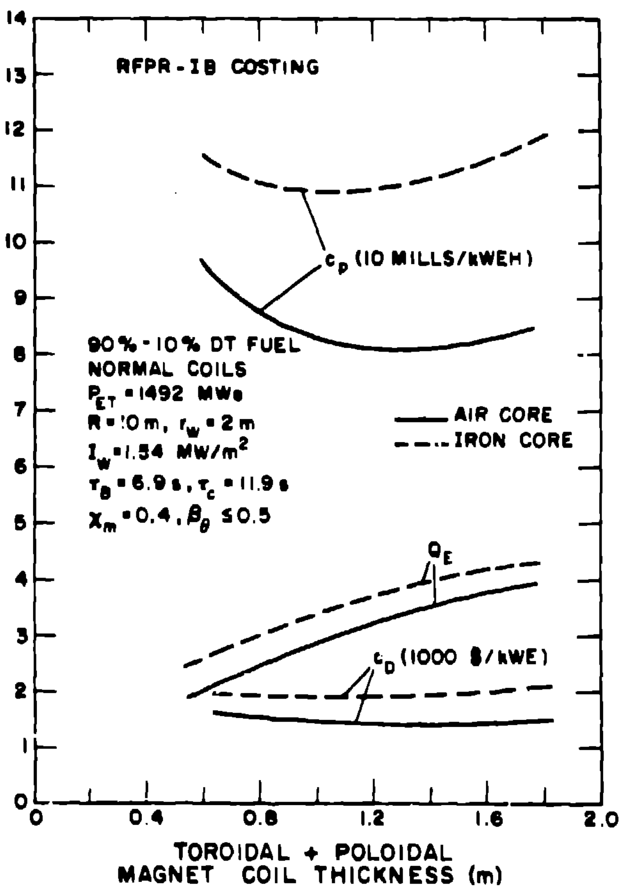

FIGURE 4. RFPR-IB costing for a 90%-10% DT fuel mixture for which ϵ_0 control is provided by fuel burnup. Ideal MHD stability criteria allow a maximum compression of 1/x ~2.5(Θ = 8, F = -2). Air- and iron-core poloidal systems with normal conducting coils are compared on a cost basis.

use of pulsed-superconducting coils has been given impetus. The superconducting mode of operation is designated as RFPR-II.

The state-of-the-art superconducting cable[13] proposed for RFPR-II (94% copper and 6% NbTi) operates at an average current density of 17 MA/m^2. Use of superconductors requires the addition of ~1-m thick (stainless steel and B_4C) radiation shield.[16] Optimized costs and Q_E for the designs with superconducting coils and normal-conducting coils are summarized in Table I. Significant increases in Q_E and reductions in cost result for all RFPR-II designs, except for the iron-core 50%-50% DT fuel system in which ohmic losses made an insignificant contribution to the energy balance. Using an air-core poloidal field system and superconducting poloidal/toroidal field coils projects to a minimum-cost RFPR system.

C. Impact of Physics Considerations on System Design

Previous RFPR designs have been subjected to stability criteria dictated by ideal MHD

TABLE 1. Optimized Cost Summary for a Range of RFPR Conceptual Designs[a]

	Iron Core		Air Core	
	Normal Coils RFPR-I	Superconducting RFPR-II	Normal Coils RFPR-I	Superconducting RFPR-II
50%-50% DT:				
Q_E	2.80	3.32	2.65	4.31
c_D($/kWe)	1950	2290	1550	1300
c_p(mills/kWeh)	110	130	89	73.6
90%-10% DT:				
Q_E	3.60	6.05	3.40	7.83
c_D($/kWe)	1930	1811	1420	1150
c_p(mills/kWeh)	109	103	81	65.5

(a) It is emphasized that the costing procedure adopted here is intended only for the intercomparison of RFPR design options and should not be used to make economic comparisons with existing energy systems on the basis of present cost.[15]

theory.[6] As discussed in Section II, a more conservative criteria would specify operation near the state of minimum energy.[8-11] Ideal MHD theory allows the pinch parameter $\Theta = B_\theta(r_w)/\langle B_z\rangle \simeq 8\text{-}10$ and $F = B_z(r_w)/\langle B_z\rangle \simeq -2.0$ during the burn,[6] while operation near minimum energy implies $\Theta \sim 2.0$ and $F \sim -0.75$. The impact of varying Θ on the costs of the RFPR-II design is shown in Fig. 5 using the minimum cost case from Table I. The pinch parameter Θ (during the burn) has been varied by changing the first-wall radius r_w while otherwise maintaining identical plasma and reactor parameters during the burn. The aspect ratio R/r_w is varied to maintain the net electric power at 1000 MWe. The dramatic increase in cost as Θ is varied from 8 to 2 is a direct consequence of decreasing Q_E.[1,2] As the first wall is moved closer to the plasma less expansion is allowed after the burn period, resulting in larger dissipation of trapped field energy during the plasma quench for a given thermonuclear yield. The assumption that all of the trapped field thermally dissipates after the burn is crucial to in the results shown in Fig. 5. Decreasing the cost while keeping $\Theta = 2$ requires an even more prolonged burn and a high burnup. This question is addressed below.

D. RFPR-II Design

In order to achieve high burnup the Culham RFPR design[14] assumed the existence of a limiting beta $\beta_{\Theta L}$. When $\beta_\Theta < \beta_{\Theta L}$ transport is taken as classical, whereas for $\beta_\Theta > \beta_{\Theta L}$ instabilities grow and saturate, appearing as enhanced loss proportional to $\exp((\beta_\Theta - \beta_{\Theta L})k)$. The value of k is sufficiently large for $\beta_{\Theta L}$ not to be exceeded by more than a few percent at any time during the burn. A physical model which may lead to a similar behavior has been studied by Christiansen and Roberts[17] while modeling previous (ZETA) and proposed (RFX) experiments. Low shear near the centerline is expected to produce a region in which Suydam stability is likely to be violated, resulting in

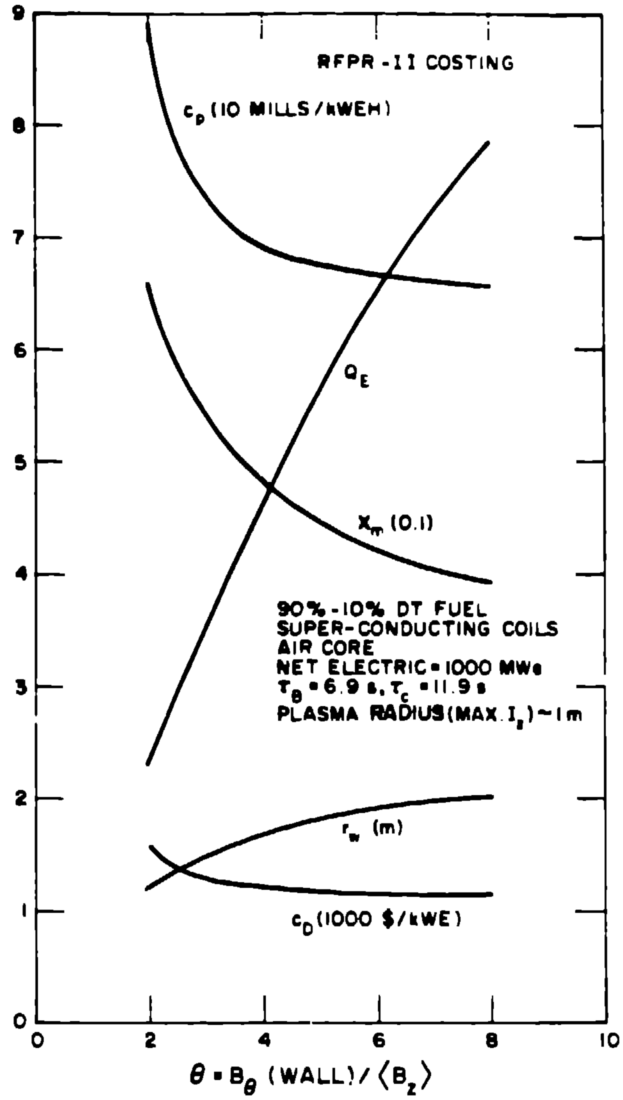

FIGURE 5. RFPR-II costing for a 90%-10% DT fuel mixture in which β_Θ control is provided by burnup. The effects on cost and recirculating power of decreasing $\Theta = B_\theta(r_w)/\langle B_z\rangle$ from 8.0 (allowed by ideal MHD theory) to 2.0 (consistent with minimum energy considerations[11]) is shown. A minimum cost system that employs superconducting coils and an air-core poloidal system is used for this example.

a turbulent central core. Confinement in this case is dictated by a stable outer annulus in which the overall loss rate is likely to be determined by electron losses. The problem, therefore, reduces to one of describing these anomalous electron losses. This penomena is also under investigation in the reactor context.[18] The same exponential loss mechanism is assumed in Ref. 18 as for the Culham reactor calculations,[14] although, fueling is also included in order to enhance the fuel burnup for a given burn pulse. These studies will hopefully better quantify the assumed loss mechanisms.

Although refueling may be technologically feasible, loss of confinement may depend on the resistive dissipation of the trapped B_z flux[17] which has a time constant given as $\tau_\eta \sim 100\ r_w^2 T_e^{3/2}/\ell n\Lambda$ using the classical value of resistivity. Taking $r_w = 1$ m, $T_e = 20$ keV, and $\ell n\Lambda = 20$ gives $\tau_\eta = 450$ s; requiring the energy dissipation to be less than 10% gives an allowable burn time of 45 s. The characteristic time for fuel burnup f_B in a batch burn of constant temperature and initial density n_o is $\tau_B = 2f_B/[n_o\langle\sigma v\rangle(1-f_B)]$. Substituting representative reactor parameters of $n_o = 3(10)^{20}/m^3$, $f_B = 0.5$, and $\langle\sigma v\rangle = 4.3(10)^{-22}\ m^3/s$ at 20 keV gives $\tau_B = 15$ s which is comparable to the field dissipation time. The field configuration, therefore, may not be maintained sufficiently long to make refueling possible. Wesson and Sykes[19] have shown on the basis of MHD calculations that the inside B_z flux may be replenished by turbulence, although, the resultant plasma loss is unknown; and until better quantified, these questions have lead LASL to use a batch burn.

A best estimate for the rate of anomalous transport expected in the reactor regime is used here. The present level of understanding of these processes allows at best a guess at τ_E in terms of a Bohm time $\tau_{Bohm} = r_w^2 B_\theta/63\ T_e$, where mks units are used. An energy confinement time for many tokamaks, including T-10,[20] at $T_e \sim 1$ keV obeys the relationship $\tau_E \sim 3.6\ r_w^2 B$, which predicts that $\tau_E \sim 225\ \tau_{Bohm}$. On the other hand, empirical "Alcator scaling"[21] predicts for $\beta_\Theta \sim 1$ that $\tau_E \sim 5.0(r_w B)^2/T_e$, which at $T_e \sim 1$ keV gives $\tau_E \sim 310\ \tau_{Bohm}$. Neither of these empirical scaling laws, which are applicable to relatively collisional plasmas, is expected to be extendable to the reactor regime, but are cited here only to give an estimate of τ_E in terms of τ_{Bohm}. For the purposes of this study, τ_E/τ_{Bohm} is taken to be 200, and the results based thereon will not be significantly altered by changes of ~ 2 in this factor. This kind of scaling is expected in a toroidal reactor system in which field inhomogeneities will have a pronounced effect on the collisionless, high temperature electrons. Considerable theoretical and experimental uncertainties are associated with this "rationalized" assumption that $\tau_E = 200\ \tau_{Bohm}$, as with the assumption of a limiting $\beta_{\theta L}$.

A burn cycle based upon $\tau_E = 200\ \tau_{Bohm} = 3.2\ r_w^2 B/T_e$ is shown in Fig. 6 for 50%-50% RFPR-II parameters. A remarkable degree of thermal stability is exhibited. The burn is terminated when the ion temperature drops below 8 keV. For this case a burnup f_B 50% results with a plasma current of 20 MA and maximum poloidal beta $\beta_\Theta = 0.37$. A plot of F versus Θ is also shown in Fig. 6 for the High-Beta Model[11] (minimum high-β energy configuration); the actual trajectory in F-Θ space followed during the burn is also shown. The poloidal field B_Θ is increased sinusoidally (0.1 s quarter period) on the same timescale that the external B_z field is completely reversed. Both fields are then held constant during the burn. The resultant F-Θ profile is in good agreement with the High-Beta Model[11] and could be improved if complex field programming is used.

The power cost c_p(mills/kWeh), direct-capital costs c_D(\$/kWe), and Q_E are shown in Fig. 7 for the RFPR-II (superconducting coils) design using an air-core poloidal transformer with bipolar current change. In all cases an average first-wall loading (14.1 MeV neutrons) of 2.5 MW/m^2 results, producing a system with a net electric power of 1000 MWe. Because of

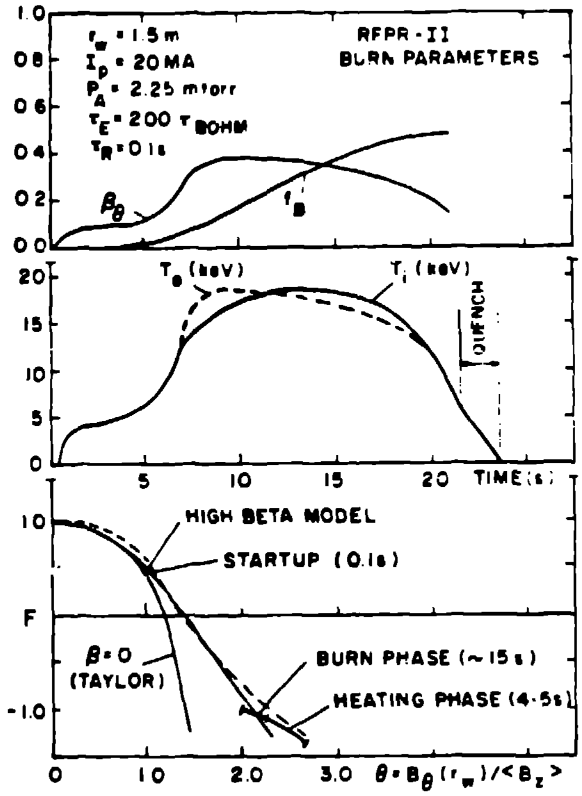

FIGURE 6. RFPR-II (superconducting coils, air-core system) burn parameters using an energy confinement time $\tau_E = 200\ \tau_{BOHM}$. The burn trajectory is in good agreement with that required by the High-Beta Model[11] for a minimum-energy configuration.

the high fuel burnup, Q_E is relatively large, and low power costs of 53 mills/kWeh at r_w = 2 m are indicated. Increases in Q_E as r_w is increased primarily results from higher burnup (f_B = 0.48 at r_w = 1.5 compared to f_B = 0.55 at r_w = 2.0).

An interim design point with a first-wall radius r_w = 1.5 m is chosen. A total blanket, shield, and coil thickness of ~2 m results in an outer radius (outside the poloidal coil) of 3.5 m which should not present construction and maintenance problems with the major radius R = 12.8 m. Larger first-wall radii lead to small major radii (for a fixed 1000 MWe) and probable increased construction and maintenance problems that the costing formalism presently does not assess. Design parameters for the 1.5-m radius reactor are listed in Table II. A

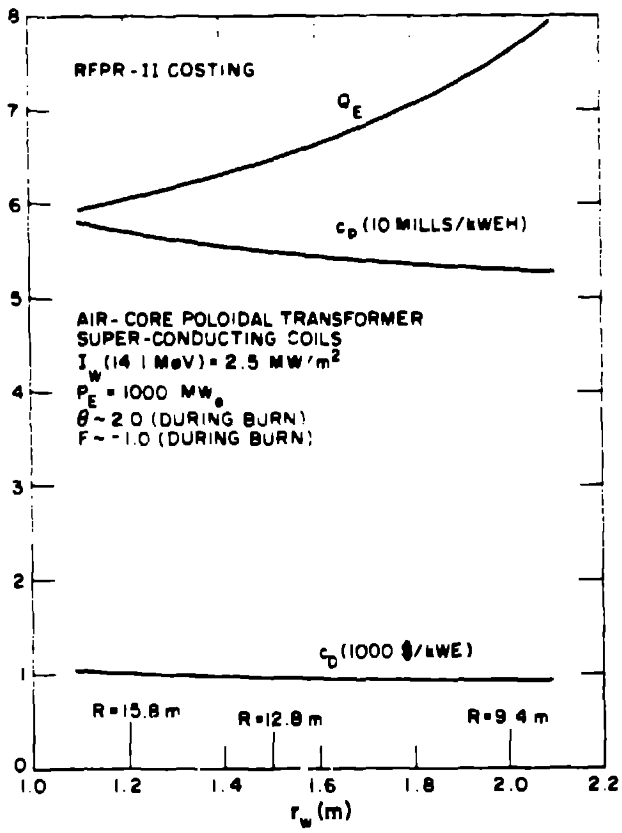

FIGURE 7. RFPR-II (superconducting coils, air-core system) costing for the case shown in Fig. 6. This case is based on minimum-energy considerations given by the High-Beta Model[11] (Θ = 2.0, F = -1.0 during the burn). Achieving a controlled burn and higher burnup (50%) $\tau_E = 200\ \tau_{BOHM}$ has resulted in a 40% cost reduction when compared to the 90%-10% DT case in Fig. 5.

corresponding summary of all major costs are shown in Fig. 8. The reactor plant equipment costs comprise approximately 50% of the total direct plant costs, whereas the costs associated with the reactor *per se* amount to 24% of the total direct cost.

IV. CONCLUSIONS

An interim design point has been reported for a 1000 MWE(net) Reversed-Field Pinch Reactor (RFPR-II) with a first-wall radius of 1.5 m and major radius of 12.8 m. Cost optimization has lead to an air-core poloidal transformer with bipolar current change; this approach minimizes the amount of external energy storage (homopolar

TABLE 2. RFPR-II Interim Design Summary: Air-Core Poloidal Transformer, Superconducting Coils

Symbol	Definition	Value
r_w	first-wall radius (m)	1.5
R	major radius (m)	12.8
I_c	poloidal coil current (MA)	23.4
I_p	plasma current (MA)	20.0
j_z	toroidal current density (MA/m^2)	5.4
P_A	filling pressure (mTorr)	2.25
f_B	burnup	0.48
$n\tau$	Lawson parameter (10^{20} s/m^3)	40.6
W_{TOR}	required toroidal coil energy (GJ)	2.33
W_{POL}	required poloidal coil energy GJ)	3.15
τ_B	burn time(s)	21.3
τ_C	cycle time(s)	26.3
I_w	average 14.2 MeV wall loading(MW/m^2)	2.46
Q_E	1/recirculating power fraction	6.5
η_p	plant efficiency	0.34
P_{TH}	total thermal power (MWt)	2950
p_{TH}	thermal power density (MWt/m^3)	0.90
P_{ET}	gross electric power (MWe)	1180
P_E	net electric (MWe)	1000
c_D	direct investment cost (\$/kWe)	970
c_T	total investment cost (\$/kWe)	2400
c_p	power cost (mills/kWeh)	55

(a) Based on θ_c control provided by anomalous radial transport with $\tau_E = 200\ \tau_{Bohm} = 3.2\ r_w^2 B/T$.
(b) Based on volume enclosed by and including superconducting coils.

generator) and the current flowing in the coil. A cost advantage also results when superconducting coils are used. The technology for the pulsed superconducting coils (1-3 T peak, 30 T/s) appears near term. A recirculating power fraction $\varepsilon = 0.15$ results in a net plant efficiency

$\eta_p = \eta_{TH}(1-\varepsilon) = 0.34 (\eta_{TH} = 0.4)$. This cost optimized design point predicts a power cost of $c_p = 55$ mills/kWeh and an installed capital cost of 970 \$/kWe; these cost values should be used only for intercomparison of systems using the same economic analysis.[15]

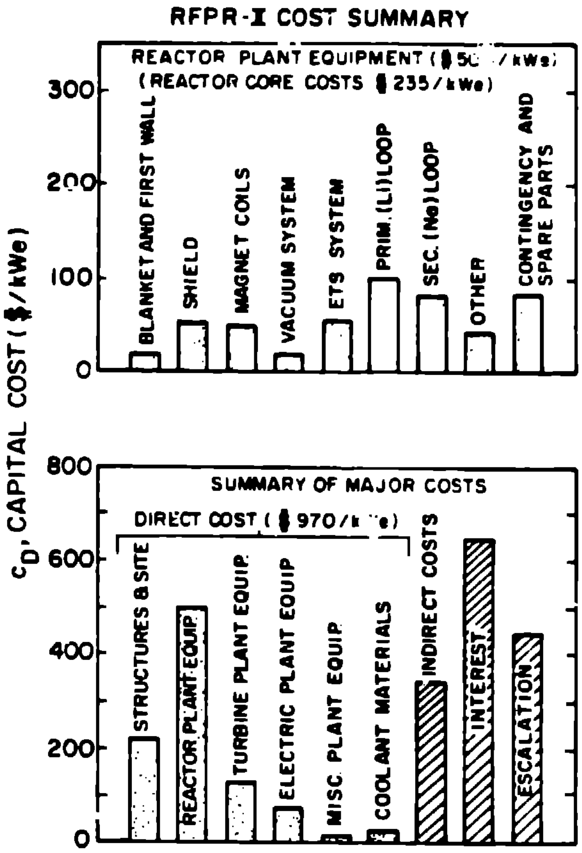

FIGURE 8. Summary of major capital costs for the interim (superconducting coils, air-core system) design point summarized in Table II.

The interim RFPR design is based on a burn trajectory that closely follows the predictions of the High-Beta Model[11] for a minimum energy plasma. The MHD stability during the extended burn times required for a significant energy gain presents a major uncertainty for the projection of any magnetic confinement scheme into the reactor regime. Alfven propagation speeds of 10^7 m/s for reactor parameters imply the plasma will rapidly seek out a minimum energy state. As for the tokamak, the existence of minimum energy states in the RFPR lends considerable credibility to this approach. The sinusoidal startup (0.1 s) closely follow the minimum energy state and ultimately settles at $\Theta = 2.0$ and $F = -1.0$ during the constant-current burn. The degree to which the burn trajectory must follow these predicted by minimum energy calculations is presently unknown. Until experiments prove otherwise, reactor-scale times which encompass 10^8 - 10^9 MHD growth times probably will require operation close to a minimum energy state, despite the fact that detailed stability computations show stable states exist far from a minimum-energy state.

A batch-burn fuel cycle is proposed for all RFPR calculations. This option has not been selected because of the re-fueling technology required of beam or pellet injection. Instead, resistive dissipation of the toroidal-field energy trapped inside the plasma may dictate the maximum allowable confinement time. The time required for resistive dissipation of 10% of the field energy at 20 keV is comparable to the time necessary to achieve a high burnup in the batch-burn mode. Turbulence or internally-generated currents may increase this resistive loss time. Until dissipation can be better quantified, refueled burns are not considered for the RFPR.

In summary, the relationship between stability and the departure from a minimum energy state represents a major issue insofar as energy confinement and the maintenance of field profiles is concerned. The evolution of the RFPR design towards an extended batch-burn operating mode that seeks to satisfy minimum-energy constraints reflects an attempt to address this issue.

IV. REFERENCES

(1) R. L. Hagenson, R. A. Krakowski, and K. I. Thomassen, "A Toroidal Fusion Reactor Based on the Reversed-Field Pinch (RFP)," IAEA Workshop on Fusion Reactor Design, Madison, Wisconsin (1977).

(2) R. L. Hagenson, "A Toroidal Fusion Reactor Design Based on the Reversed-Field Pinch," Ph.D. Dissertation, Iowa State University (1978).

(3) S. C. Schulte and J. R. Young, Battelle (Pacific Northwest Laboratories) Report PNL-SA-6648 (1977).

(4) H. A. B. Bodin, Third Topical Conference on Pulsed High Beta Plasmas, Culham, UK, pp. 39-57 (1975).

(5) C. Mercier, Nucl. Fus., 1, pp. 47-53 (1960).

(6) D. A. Baker and J. N. DiMarco, USERDA Rept. LA-6177-MS (1975).

(7) J. D. Lawson, UKAEA Rept. CLM-R171, Culham Laboratory (1977).

(8) J. B. Taylor, Phys. Rev. Letters 33 (19), pp. 1139-1141 (1974).

(9) J. B. Taylor, Fifth IAEA Conf. on Plasma Physics and Controlled Fusion, Tokyo, Japan, 1, pp. 161-167 (1974).

(10) J. B. Taylor, Third Topical Conference on Pulsed High Beta Plasmas, Culham, UK, p. 59 (1975).

(11) A. A. Newton, Li Yin-An, J. W. Long, and B. C. Yeung, Third Topical Conference on Pulsed High Beta Plasmas, Culham, UK, pp. 323-328 (1975).

(12) K. I. Thomassen, et al., EPRI (Electric Power Research Institute) ER-246, Project 469 (1976).

(13) D. Weldon and J. Wollen, personal communication, Los Alamos Scientific Laboratory (1978).

(14) R. Hancox and W. R. Spears, UKAEA Rept. CLM-R 172 Culham Laboratory (1977).

(15) S. Schulte, personal communication, Battelle, Pacific Northwest Laboratories (1978).

(16) M. A. Abdou, USERDA Rept. ANL/CTR/TM-51 (1975).

(17) J. P. Christiansen and K. V. Roberts, Nucl. Fus., 18 (2), pp. 181-196 (1978).

(18) R. Nebel and G. H. Miley, "Refueling and Control of RFP Burns," Fusion Studies Laboratory, University of Illinois, this conference (1978).

(19) A. Sykes and J. A. Wesson, Phys. Rev. Letts., 37, p. 140 (1976).

(20) A. B. Berlizov, et al., Sixth Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, 1, pp. 3-18 (1976).

(21) E. Apgar, et al., ibid, pp. 247-266.